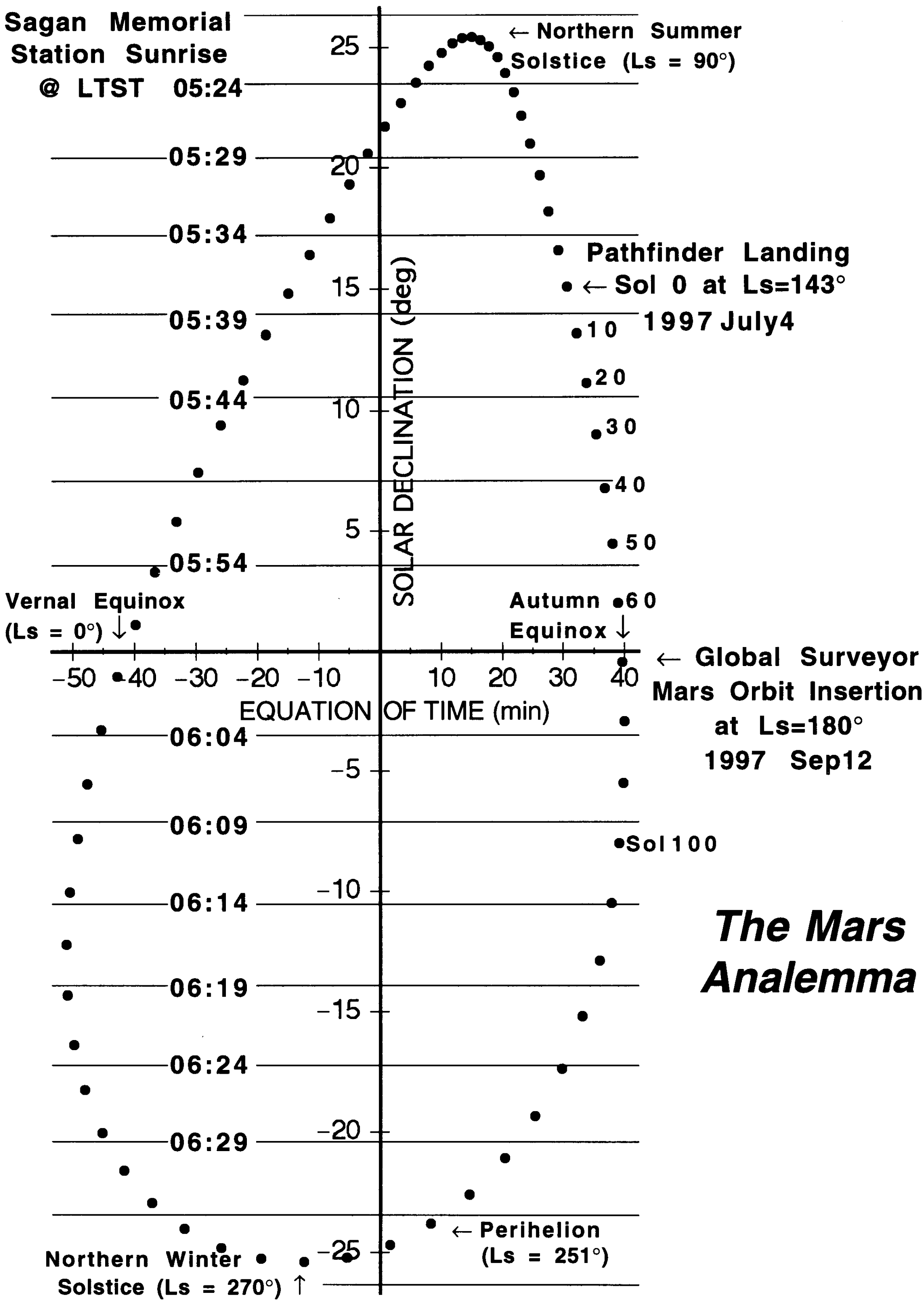
Geophysical Research Letters



The Mars Analemma

AUGUST 15, 1997

Volume 24 Number 16

AMERICAN GEOPHYSICAL UNION

GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 16, PAGES 1967-1970, AUGUST 15, 1997

Accurate analytic representations of solar time and seasons on Mars with applications to the Pathfinder/Surveyor missions

Michael Allison
NASA/Goddard Institute for Space Studies; 2880 Broadway; New York, NY

Abstract. Efficient analytic recipes are presented for a moderately accurate, closed-form calculation of the areocentric longitude (Ls), analemmic "equation of time," and solar hour angles on Mars, along with an approximate recovery of the Viking "Local Lander Time." The adopted fit to the fictitious mean sun implies a Mars tropical orbit period of 686.9725^{d}.

Introduction

The passage of Mars solar time and seasons is a combined function of the planet's rotation, obliquity, and anomalistic motion along its eccentric orbit. No other planet in the solar system exhibits such a pronounced and pervasive response to the diurnal/seasonal modulation of temperature, winds, and surface pressure, with attendant variations in water vapor, atmospheric opacity, boundary layer, ground frost, and polar caps.

The accurate calculation of the solar hour angle is a much more critical issue for Mars weather mapping than it is for the Earth, not only on account of the planet's five-times larger orbital eccentricity, but also as a result of the very rapid cooling of its relatively thin atmosphere. The "Golitsyn number" ratio of the diurnal period to the radiative time constant is over 10 times larger for Mars than for the Earth, with a roughly commensurate relative amplitude for the solar/tidal signal.

Compilations of the areocentric longitude (Ls) and solar illumination at Mars are published in *The Astronomical Almanac* (*AA*) by the U.S. Naval Observatory (USNO). Similar information can be generated with the Multiyear Interactive Computer Almanac (*MICA 1990-1999*), also provided by the USNO, or with The Jet Propulsion Laboratory (JPL) Navigational Ancillary Information Facility (NAIF) software, both based on the JPL ephemerides taking account of the N-body interactions among the planets. And Meeus (1995) presents the Mars (hundredth-day) equinox and solstice dates for the years 1646 to 2060, as computed with the high-precision ("VSOP87") theory of Bretagnon and Francou (1988).

Definitions of Mars solar coordinates as adopted for current spaceflight missions have been recorded in JPL internal office memoranda (e.g. Blume, 1986; Lee, 1995) but rely on a read-out of computational ephemerides either inaccessible or only awkwardly adapted to off-line planetary science studies. A NASA technical memorandum (Kaplan, 1988) appears to offer the only published reference to the recommended definitions, but with outdated orbital/rotational elements. Although analytic formulae for the moderately accurate calculation of the Earth-Solar hour angles can be found in Yallop and Hohenkerk (1992) and elsewhere, similar recipes for Mars have so far been lacking.

Analytic Mars/Solar Ephemeris

The daily/hourly advance of the Mars seasons and solar right ascension can be prescribed in terms of the mean anomaly $M \equiv L - \varpi$, or mean longitude with respect to the perihelion, and the right ascension of the "fictitious mean sun" α_{FMS} representing the departure of the true areocentric solar longitude L_s, as referenced to the planet's vernal equinox, from the "equation of the center" $(v - M)$, itself the difference between the true and mean orbit anomalies. In terms of these elements, the following algorithm provides a moderately accurate, closed-form representation of L_s, the solar right ascension and (planetographic) declination, α_s and δ_s, along with an approximate representation of the Mars heliocentric distance and longitude, r_M and λ_M. As referenced by the elapsed time from the J2000 epoch (2000 Jan 1.5), with $\Delta t_{J2000} \equiv (JD - 2451545.0)$,

$$M = 19°.41 + (0.5240212°/d)\bullet\Delta t_{J2000} \quad (1)$$

$$\alpha_{FMS} = 270°.39 + (0.5240384°/d)\bullet\Delta t_{J2000} \quad (2)$$

$$\begin{aligned} L_s = \alpha_{FMS} &+ (10°.691 + 3°.7 \times 10^{-7} d^{-1} \Delta t_{J2000}) \sin M \\ &+ 0°.623 \sin 2M + 0°.050 \sin 3M + 0°.005 \sin 4M \end{aligned} \quad (3)$$

$$\begin{aligned} \alpha_s = L_s &- 2°.860 \sin 2L_s + 0°.071 \sin 4L_s \\ &- 0°.002 \sin 6L_s \end{aligned} \quad (4)$$

$$\delta_s = \sin^{-1}(0.4256 \sin L_s) + 0°.25 \sin L_s \quad (5)$$

$$\begin{aligned} r_M = 1.5236(&1.00436 - 0.09309 \cos M \\ &- 0.00436 \cos 2M - 0.00031 \cos 3M)\mathrm{AU} \end{aligned} \quad (6)$$

$$\lambda_M \approx L_s + 85°.06 + (0.000029°/d)\bullet\Delta t_{J2000} \quad (7)$$

Then reset each needed angle within 0–360° as e.g.

$$L_s \rightarrow \mathrm{FractionalPart}[1 + \mathrm{FractionalPart}[\frac{Ls}{360°}]]360° \quad (8)$$

The given definition of the mean anomaly in Eqn. (1) is derived from the mean element representations of L and ϖ by Standish *et al.* (1992), based on a numerical integration of the JPL ephemerides over the years 1800–2050. The corresponding fictitious mean sun defined by Eqn. (2) represents a consistent fit over 120 Mars orbits (from 1834 to 2060) to the equinox and solstice seasons calculated by Meeus (1995). This recovers the α_{FMS} determinations by Blume (1986) and Lee (1995) on behalf of the Mars Observer and Global Surveyor Projects for their intended epochs to within 0.01°, but takes a slightly smaller mean motion (or larger period) than for their fit to a readout of the JPL ephemerides over the anticipated course of these missions. [Comparison with the specified FMS = –28°.217 + 0.524041(°/d)ΔT in Kaplan (1988) reveals an apparent typographical error. For ΔT the elapsed days since 1993 August 1.0 as indicated, Kaplan's formula gives good agreement in the corrected form FMS = –2$\underline{3}$8.217° + 0.524041(°/d)ΔT.]

Eqn. (3) derives from a series approximation to the "equation of the center," carried to fourth order in the orbital eccentricity (Taff, 1985), and provides an analytic representation of the nonlinear progression ΔLs of the areocentric longitude shown in Fig. 1 of Kieffer *et al.* (1992). The orbital eccentricity, 0.0934 for the current epoch, increases at a rate of 1.2×10^{-4} per century, contributing the included $\sim 3.7 \times 10^{-7}$°/d long-term advance of the solar longitude. The algorithm recovers the seasonal calculations by Meeus (1995) to better than 0.04° in the areocentric longitude for the 200 year interval 1850–2050, while comparison with the *AA* shows agreement within 0.02° for current epochs.

Eqn. (4) is based on an expansion of the "reduction to the equator" $(L_s - \alpha_s)$ to a sixth-power dependence on the tangent of

Paper number 97GL01950.

Table 1. Mars mean orbit and rotation elements (J2000).

Element	Symbol	Numerical Value
Perihelion Date (mean element)	t_p	1999 Nov 25.46 = JD 2451507.96
Areocentric longitude of Perihelion	L_{sp}	250°.98
Anomalistic Year (perihelion-to-perihelion)	τ_{anom}	686.9951^d = 668.6141^{sol}
Tropical Year (fictitious mean sun)	τ_{trop}	686.9725^d = 668.5921^{sol}
Mars Solar Day	sol	$24^h39^m35.244^s$ = 1.02749125^d
Orbital Eccentricity	e	0.0934 + $0.00012/d^{post\text{-}J2000}$
Orbital longitude of Perihelion	ϖ	336°.04 + $0°.000012/d^{post\text{-}J2000}$
Mean Solar Distance (semi-major axis)	a	1.52366 AU = 2.27936×10^8km
Obliquity (Eqtr to Orbit)	ε	25°.19
Prime Meridian from the Mars V.E.	V_m	313°.6975 +$350.8919851°/d^{post\text{-}J2000}$

(one-half) the obliquity ε (Smart, 1962). Although a fixed value of ε = 25°.19 has been assumed, the included small difference in the anomalistic and tropical orbit motions as given by Eqns. (1) and (2) accounts for the precessional advance of the areocentric longitude over successive orbits. Eqn.(5) includes a small (0°.25 or less) correction to the planetographic declination as measured with respect to the oblate surface of the planet, assuming a geometrical flattening of 0.006 (Smith and Zuber, 1996). Eqn. (6) for the radial distance excludes any account of heliocentric latitude β, as for the ecliptic projected ("curtate") solar distance $r_{EP} = r\cos\beta$, but with β no larger than the (1°.85) inclination of Mars, $|r - r_{EP}|$ is everywhere less than one-thousandth of an A.U. The neglected change in the mean solar distance is itself less than one part in ten-thousand over 200 years (Standish *et al.*, 1992). Eqn. (7) for the heliocentric longitude (Ls + ϖ – Lsp) neglects the projected "reduction to the ecliptic," of order $\tan^2(i/2)$, everywhere less than 0.02°, but takes account of the advance of the perihelion.

Table 1 provides an alternate numerical representation of the Mars mean orbit and rotation elements as adopted by the algorithm. The indicated 686.9725^d Mars tropical year corresponds to the daily rate for the fictitious mean sun. The exact interval for the orbital repetition necessarily varies, however, with the choice of L_s, as prescribed by Eqs. 1–3. The associated period for the successive passage of the vernal equinox, for example, is approximately 686.971^d, consistent with the (1870-2049) dates derived by Kieffer *et al.* (1992) from the USNO ephemerides. (There is a similar ambiguity regarding the Earth's tropical year, given as 365.2422^d for the fictitious mean sun, whereas the vernal-equinox period is more nearly 365.2423^d.)

For some purposes it is also useful to have a quick recipe for the time of a particular areocentric longitude. An approximate functional expression for the Julian Date of season Ls within the nth orbit of Mars since the 1996 August 26 Vernal Equinox, is

$$\mathrm{JD}(Ls,n) = 2451029.0 + 1.90826(/°)Ls - 20.42\sin(Ls - 251°) + 0.72\sin 2(Ls - 251°) + 686.97\bullet\mathrm{IntegerPart}[n-1]. \quad (9)$$

With n=0 this retrieves the seasonal dates for the Pathfinder mission, while n = –11 recovers the first year of the Viking era (but only to the nearest tenth day within ±25 yrs of the present).

Clock Time and Hour Angles

The seasonally variable deviation between the uniformly moving fictitious mean sun and the true solar right ascension owing to the eccentricity of a planet's orbit and the obliquity of its pole vector is defined as the "Equation of Time," EOT = $\alpha_{FMS} - \alpha_s$, and given by the algorithm listed above for Mars as

$$\mathrm{EOT} = 2°.860\sin 2L_s - 0°.071\sin 4L_s + 0°.002\sin 6L_s - \{(10°.691 + 3°.7\times10^{-7}d^{-1}\Delta t_{J2000})\sin M + 0°.623\sin 2M + 0°.050\sin 3M + 0.005°\sin 4M\}. \quad (10)$$

The EOT may then be converted to solar minutes by a multiplication of 4 (minutes/°). Since the right ascension of the true sun (α_s) really corresponds to $\tan^{-1}(\cos\varepsilon\,\tan Ls)$, the error of the given EOT recipe is comparable to the error in the associated L_s (equivalent to about ±10 sec of "clock time").

The variation of the EOT in Mars minutes over the solar seasonal cycle is shown in Fig. 1, along with the implied ongoing change in the length of the true solar day in Mars seconds. The EOT is zero at Ls = 57.7° and 258.0° for the current epoch, with a maximum of 39.9 minutes at Ls = 187.9° and a minimum of –51.1 minutes at Ls = 329.1°. Equivalently, the true Sun on Mars varies from 10° west of the FMS just after the Autumnal equinox to nearly 13° east in the northern mid-winter. On the Earth, for comparison, the EOT varies only between –14.2 and +16.3 minutes.

Figure 2 presents the related Mars "analemma," a parametric plot of the Equation of Time vs. the solar declination, as previously computed by Harvey (1982) for each planet in the Solar System. The Martian analemmic teardrop may be compared with the corresponding "figure-8" pattern for the Earth, as shown on some globes. The difference owes both to the over fives times larger eccentricity of Mars as well as the occurrence of its perihelion prior to rather than after the solstice.

Once calculated, the Equation of Time may be referenced as the difference between the true solar time and the mean solar time. And local (true or mean) solar time is then defined by the difference in right ascension between a given location and the (true or mean) Sun. Blume (1986) has recommended the adoption of these conventional definitions as the basis for time scales on Mars, as appropriate to spacecraft reconnaissance.

The practical calculation of the daily clock time requires a specific calibration with respect to the planet's vernal equinox of the Prime Meridian running through the small crater "Airy–0" in the Terra Meridiani region. Davies (1977) determined this with respect to the J1950 epoch from triangulated Mariner 9 images and preliminary Viking Lander radio tracking. The indicated definition in the table appropriate to J2000 represents a small forward adjustment (by approximately 0°.30) of the value currently adopted by the *AA*, consistent with the recently reported fit to six years of Viking Lander tracking data by Yoder and Standish (1997) who specify the Mars prime meridian as

$$V_m = (252°.3003 - 180°) + 350°.8919851(\mathrm{JD} - 2444239.5) \quad (11)$$

plus modeled seasonal variations ~ 2 milli-arcsec. (The 180° shift as included here is required for the transformation from a sun-centered to a planet-centered reference to the Mars equinox.)

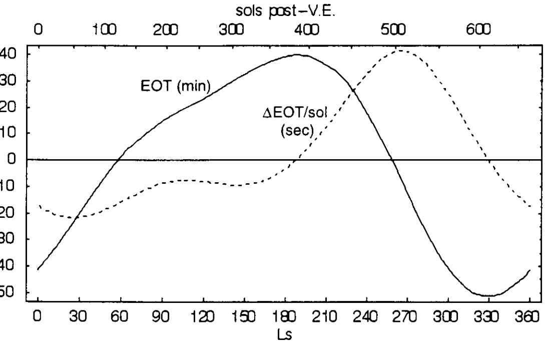


Figure 1. The Equation of Time (EOT) in Mars minutes over even increments of the areocentric longitude Ls (plotted as the solid curve) and the variation in the length of the true solar day in Mars seconds (dashed). The corresponding number of Mars sols elapsed post-equinox is indicated along the top.

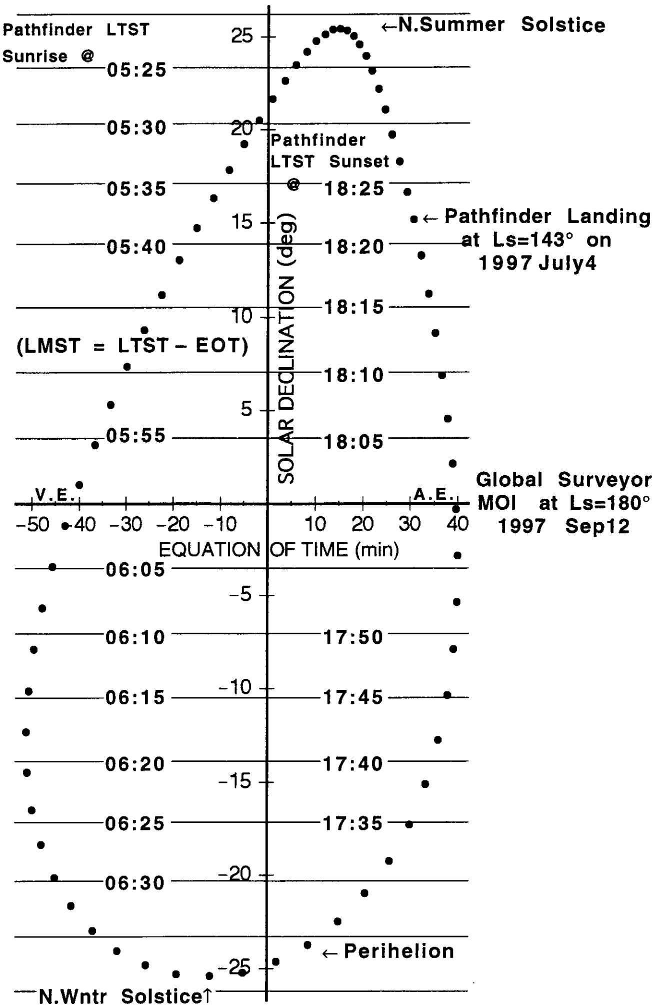


Figure 2. The Mars analemma, showing the variation of the solar declination (in deg) along the vertical axis with the Equation of Time (in min) along the horizontal axis for the marked clockwise advance of 10-sol intervals over one orbit. Approximate LTSTs for sunrise/sunset in 5 min intervals at the Pathfinder target site are indicated by the grid.

The Mean Solar Time on the Mars prime meridian as measured with respect to 0^{hr} "midnight" is then given as

$$\mathrm{MST}=\mathrm{FractionalPart}[(V_m-\alpha_{FMS}+180°)/360°]24^{\mathrm{Mars\ hr}}. \quad (12)$$

Once calibrated with respect to a particular epoch, the conversion of a date and hour in Terrestrial Time amounts to the calculation of the appropriate remaindered fraction of the Mars) solar day, related to the sidereal rotation period as $d_{sol} = d_{sid}/(1 - d_{sid}/\tau_{trop})$. With $d_{sid} = 24^{hr}37^{m}22.663^{s}$ and $\tau_{trop} = 686.9725$ day, the Mars mean solar rotation period is evaluated as 1.02749125 day.

As simplified by reference to a specific occurrence of the Mars prime meridian midnight established prior to any time of current interest (e.g. 1970 April 15 at 12:00 noon Terrestrial Time), the mean solar time formula can then be prescribed as

$$\mathrm{MST}=\mathrm{FractionalPart}[(\mathrm{JD}^{TT}-2440692.000)/1.02749125]24^{hr}. \quad (13)$$

Then the Mars *local mean solar time* at some longitude Λ_W on the planet (measured westward from the prime meridian according to the planetary cartographic convention in the range 0–360°) can be evaluated as

$$\mathrm{LMST} = \mathrm{MST} - \Lambda_W(24\mathrm{hr}/360°) \quad (14)$$

and the *local true solar time* as

$$\mathrm{LTST} = \mathrm{LMST} + \mathrm{EOT}\bullet(\mathrm{hr}/15°). \quad (15)$$

In practice each hour angle should be reset to $0–24^{hr}$ as, e.g.

$$\mathrm{LTST}\rightarrow\mathrm{FractionalPart}[1 + \mathrm{FractionalPart}[\mathrm{LTST}/24]]24^{hr}, \quad (16)$$

and then translated as desired from fractional hours to minutes. The corresponding sub-solar (west) longitude is just

$$\Lambda_{subsol} = \mathrm{MST}\bullet(15°/\mathrm{hr}) + \mathrm{EOT} - 180°. \quad (17)$$

For the most exacting purposes, it should be noted that the given Mars hour-angle formulae have been calibrated for use with Terrestrial (Dynamical) Time (TT), or Ephemeris Time (ET) as used prior to 1984, measured in strictly even increments of SI seconds, currently defined with reference to atomic clocks. Precise applications must account for the distinction between TT and the Universal (Coordinated) Time (UTC) or the former Greenwich Mean Time (GMT), as used for civil time keeping, periodically adjusted for the variable advance of terrestrial mean solar time, largely as a result of the lunar-tidal despinning of the Earth's rotation. As of 1997, TT = UT + 63 sec (*cf.* the *AA*). An approximate correction for other times within the 1850–2050 epoch (accurate to within 4 sec for 1950–2000) is

$$\mathrm{TT} - \mathrm{UTC} = 66^{sec} + 0.95^{sec}(\Delta t_{J2000}/365.25) + 0.0035^{sec}(\Delta t_{J2000}/365.25)^2 \quad (18)$$

where again Δt_{J2000} measures the days elapsed post-J2000.

It should also be emphasized that the above equations exclude the variable (3 – 22 minute) light-time displacement τ_{ME} of Earth with respect to Mars (often comparable to the EOT) and therefore strictly apply only to Mars time as reckoned by an Earth clock transported to Mars. High-precision conversions to the elapsed proper time on Earth may eventually require some new definition of Martian Coordinate Time analogous to Barycentric Coordinate Time, accounting for the relativistic effects of orbital motion, planetary rotation, and gravitational potential. For present practical purposes, the corresponding "look-back" or Earth-observed time for a given coordinate time on Mars can be estimated as $t^{EOB} \approx t - \tau_{ME}$, where the light-time

$$\tau_{ME} = [r_E^2 + r_M^2 - 2r_E r_M \cos(\lambda_M - \lambda_E)]^{1/2}(499^{sec}/\mathrm{AU}), \quad (19)$$

with the Earth's heliocentric distance and longitude given in terms of

$$g = 357°.528 + (0.9856003°/d)\bullet\Delta t_{J2000} \quad (20)$$

as

$$r_E = (1.00014 - 0.01671 \cos g - 0.00014 \cos 2g)\mathrm{AU} \quad (21)$$

and

$$\lambda_E = 100°.472 + (0.9856474°/d)\bullet\Delta t_{J2000} + 1°.915 \sin g + 0°.020 \sin 2g. \quad (22)$$

(*cf.* page C24 of the *AA*.) As a comprehensive check on the computer-coded interpretation of the given algorithm, interested users may readily confirm that the "apparent" sub-solar longitude implied by Eqn. (17), with MST and EOT evaluated for $t - \tau_{ME}\bullet(d/86{,}400^{sec})$, consistently recovers (to approximately ±0°.01) the tabulated values on pages E65 and E67 of the *AA* plus the 0°.30 forward adjustment of the revised determination of the Mars prime meridian by Yoder and Standish (1997).

Applications to Mars Missions

Measurements from the (1976-1982) Viking Lander mission were tagged with the "Local Lander Time" or LLT. No precise definition of this can be found in the literature, however, and it has not been recovered by the Pathfinder navigation team at JPL (W.H. Blume, private communication, 1997). According to Colburn *et al.* (1989) the Viking LLT was defined so that the Sun would cross the nadir meridian at midnight on the first sol after touch-down, but otherwise took no account of the subsequent progression of the EOT. This suggests that the Viking LLT might be represented as VLLT = MST + $\mathrm{EOT}(t_{VL}) - \Lambda_{VL}(24\mathrm{hr}/360°)$, with MST the same as defined in this study, $\mathrm{EOT}(t_{VL})$ the associated equation of time on the date of landing, and Λ_{VL} the lander longitudes. The EOT was 0.287 hr for the Viking 1 landing, at t_{VL1} = JD 2442980.0 (1997 July 20.5), and 0.385 hr for t_{VL2} = JD 2443025.4 (1976 Sep 3.9), with targeted longitudes of 47.5°W for VL1 and 226°W for VL2 (Masursky and Crabill, 1976a,b). These would then imply

$$\mathrm{VL1\text{-}LLT} = \mathrm{MST} - 2.88\ \mathrm{hr} \quad (23)$$

and

$$\text{VL2-LLT} = \text{MST} - 14.69 \text{ hr}, \quad (24)$$

in good agreement (to one minute precision) with a lengthy table provided by Colburn *et al.* of measured optical depths tagged with the LLT and corresponding "fractional 1976 day number" (elapsed since JD2442777.5) over some 800 sols and with the event labels for the Viking Lander image browser at Washington University's Planetary Data Systems (PDS) node (http://wundow.wustl.edu/imdb/archive.html). A slightly different time calibration appeared in the original Viking image catalog, however, as excerpted in the Viking Lander Imaging Team's *The Martian Landscape* (1978), perhaps incorporating some variable light-time adjustment of the corresponding GMT on Earth. At any rate, the Viking lander LTST, periodically over one hour behind the adopted LLTs, could now be evaluated with the given algorithm from the corresponding Earth event times and the recovered west longitudes of 48°.26 and 226°.03, for VL1 and VL2, respectively (Yoder and Standish, 1997).

The Pathfinder spacecraft was navigated toward a Mars landing on 1997 July 4 at approximately 16:57 UTC, within a target ellipse in the Ares Vallis region centered at 33°.1 West longitude and 19°.43 North latitude, for a predicted LTST touchdown of 03:01. Sunrise/sunset, corresponding to a ±90° solar zenith angle with respect to the local normal surface at latitude ϕ, may be estimated to occur at an LTST of $12^{hr} \pm (24^{hr}/360°)\mathrm{Cos}^{-1}(-\mathrm{Tan}\phi \bullet \mathrm{Tan}\delta_s)$, where δ_s is the seasonally variable solar declination given by Eqn. (5). For the Pathfinder target latitude this may then be approximated as

$$\mathrm{LTST}_{\mathrm{Pf\ SS/SR}} \approx 12^{hr} \pm \{6^{hr} + 1.41^{min}\delta s(1 + 0.00011\delta s^2)\} \quad (25)$$

(for δs in deg). The Mars analemma may therefore be interpreted by an appropriate change in the scale for the declination axis as a charted almanac for Pathfinder sunrise/sunset, as also indicated in Fig. 2. (Exact times will depend upon the actual landing coordinates and local topography.)

Mars solar timing will also be critical to the interpretation of data from the Global Surveyor and follow-on Surveyor 98 spacecraft, both designed for pole-to-pole mapping orbits with fixed or only slowly precessed nodes with respect to the fictitious mean sun. The analysis of daily global weather maps will be an important objective of these missions, based on measurements from the Thermal Emission Spectrometer (on Global Surveyor) and the Pressure Modulator Infrared Radiometer (or PMIRR on Surveyor 98) and the data assimilation will need to account for the diurnal solar tide. Although the day/night difference in upper-level temperatures should afford some characterization of this, the atmospheric response calculated by Zurek (1976) also shows a rapid vertical variation of the hour-angle of maximum amplitude and sub-critical Richardson number (Ri<1/4, as for the onset of turbulence). The nominal 5km vertical resolution of PMIRR (*cf.* McCleese, 1992) may permit the deconvolution of this structure, but only by an accurate account of the true solar forcing including the EOT.

The daily "ΔEOT" as indicated in Fig. 1, implies a 60 sec variation in the length of the true solar day on Mars in the course of its orbit, and may itself contribute some fine-tuning adjustment to the resonant forcing of pseduo-diurnal waves plausibly detected by Tillman (1988) as annually synchronized transients in the Viking lander pressure data. One class of these occurs shortly before the global dust storms, while the other tends to occur under relatively clear conditions near the most pronounced annual surface pressure minimum, at L_s = 145°. Although the variable temperature and dust load are probably of controlling importance to the wave forcing for both seasons (*cf.* Zurek, 1988), the mid-summer episodes also coincide with the most extended interval of nearly unvarying true solar days.

Acknowledgements. I am grateful to William H. Blume of the Jet Propulsion Laboratory for sharing with me the JPL IOMs on Mars solar timekeeping which he and others in his group have prepared on behalf of the Mars Observer, Global Surveyor, and Pathfinder Projects. E. Myles Standish provided expert advice on the numerical calibration of the Mars mean anomaly and rotation angle. I thank Anthony Del Genio, Robert M. Haberle, Howard C. Houben, Larry Travis, and Richard Zurek for their helpful comments on a preliminary version of this paper.

References

The Astronomical Almanac. The U.S. Government Printing Office, Washington, D.C., 1985–1997.

Blume, W.H., Computing the fictitious mean Sun for Mars and defining Martian time scales, *JPL IOM 312/85.5-2397.* Jet Propulsion Laboratory, Pasadena, 1986.

Bretagnon, P. and G. Francou, Planetary theories in rectangular and spherical variables: VSOP87 solutions, *Astron. Astrophys., 202,* 309-315, 1988.

Colburn, D.S., J.B. Pollack, and R.M. Haberle, Diurnal variations in optical depth at Mars. *Icarus, 79,* 159-189, 1989.

Davies, M.E., The prime meridian of Mars and the longitudes of the Viking Landers, *Science , 197,* 1277, 1977.

Harvey, D.A., The analemmas of the planets, *Sky and Tel., 63,* 237-239, 1982.

Kaplan, D., *Environment of Mars, 1988. NASA TM 100470.* Washington, DC., 1988.

Kieffer, H.H., B.M. Jakosky, and C.W. Snyder. The Planet Mars: From antiquity to the present, in *Mars,* edited by H.H. Kieffer, B.M. Jakosky, C.W. Snyder, M.S. Matthews, pp.1–34, Univ. of Arizona Press, Tucson, 1992.

Lee, W., Mars fictitious mean sun and equation of time. *JPL IOM 312/95.5-4353.* Jet Propulsion Laboratory, Pasadena, 1995.

Masursky, H. and Crabill, N.L., The Viking landing sites: selection and certification, *Science, 193,* 809-812, 1976a.

Masursky, H. and Crabill, N.L., Search for the Viking 2 landing site, *Science, 194,* 62-68, 1976b.

McCleese, D.J., R.D. Haskins, J.T.Schofield, R.W. Zurek, C.B. Leovy, D.A. Paige, and F.W. Taylor, Atmosphere and climate studies of Mars using the Mars Observer pressure modulator infrared radiometer, *J.Geophys.Res., 97,* 7735-7757, 1992.

Meeus, J. *Astronomical Tables of the Sun, Moon and Planets,* Willmann-Bell, Richmond, 1995.

Smart, W.A., *Text-Book on Spherical Astronomy,* Cambridge Univ. Press, 1962.

Smith, D.E. and M.T. Zuber, The shape of Mars and the topographic signature of the hemispheric dichotomy. *Science,* **271**,184-188, 1996.

Standish, E.M., X.X. Newhall, J.G. Williams, and D.K. Yeomans, Orbital ephemerides of the Sun, Moon, and planets, in *Explanatory Supplement to the Astronomical Almanac,* edited by P. Kenneth Seidelmann, pp.279-323, Univeristy Science Books, Mill Valley, CA, 1992.

Taff, L.G., *Celestial Mechanics: A Computational Guide for the Practitioner,* John Wiley, New York, 1985.

Tillman, J.E., Mars global atmospheric oscillations: Annually synchronized, transient normal mode oscillations and the triggering of global dust storms,*J.Geophys.Res.,93,* 9433-9451, 1988.

Viking Lander Imaging Team, *The Martian Landscape.* NASA SP–425. Washington DC, 1978.

Yallop, B.D. and C.Y. Hohenkerk, Astronomical Phenomena, in *Explanatory Supplement to the Astronomical Almanac,* edited by P. Kenneth Seidelmann, Univeristy Science Books, Mill Valley, CA, pp.475-503, 1992.

Yoder, C.F. and E.M. Standish, Martian precession and rotation from Viking lander range data. *J. Geophys. Res., 102,* 4065-4080, 1997.

Zurek, R.W., Diurnal tide in the Martian atmosphere, *J. Atmos. Sci,* **33**, 321-337,1976.

Zurek, R.W. Free and forced modes in the Martian atmosphere, *J. Geophys. Res., 93,* 9452-9462, 1988.

M. Allison, NASA/Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025. (email: pcmda@giss.nasa.gov)

(Received April 8, 1997; revised June 10, 1997; accepted June 25, 1997.)

Volume 24 Number 16 August 15, 1997
GRLAJ(16) 1967–2106(1997) ISSN 0094-8276

Geophysical Research Letters

(continued on inside back cover)

Cover. *The Mars analemma, showing the solar declination on the planet and the corresponding "equation of time" (EOT) for the departure of the fictitious mean sun (FMS) from the true solar hour angle as these vary over a full Mars orbit. The clockwise seasonal advance is marked in increments of 10 Mars solar days (sols), as referenced to the Pathfinder landing, along with the indicated areocentric solar longitude (Ls), defined as 0° for the vernal equinox. The horizontal grid lines indicate the local true solar time (LTST) for sunrise in 5-min increments at the Sagan Memorial Station (latitude 19.3°N, longitude 33.5°W) in the Ares Valles, including a roughly 1-min timing correction for the apparent solar semidiameter. The aspect ratio for the plot has been chosen so that scaled intervals for the corresponding solar longitudinal displacement of the EOT in (15/60 min) degrees would match the declination increments in the same angular units.*

An accurate account of the EOT and true solar hour angle is much more important for Mars weather analysis than for analysis of the Earth's weather because Mars' orbital eccentricity is more than 5 times larger than Earth's and because the thin Martian atmosphere heats and cools much more rapidly in response to the diurnal solar tide. Although the LTST on Mars can be determined by reference to computational ephemerides, it may also be efficiently derived for use in atmospheric analysis and spacecraft experiment planning to moderate (~10 s) accuracy by an appropriate calibration of extended trigonometric series in the orbital mean anomaly and FMS. (See the paper by M. Allison, this issue.)